Neuro-Cardiovascular Responses to Sympathetic Stimulation in Fighter Pilots

Marcus Vinicius dos Santos Rangel; Grace Barros de Sá; Paulo Farinatti; Juliana Pereira Borges

INTRODUCTION: The chronic effects of regular exposure to high acceleration levels (G-force) on the neuro-cardiovascular system are unclear. We compared the mean arterial pressure (MAP) and cardiac autonomic modulation between nonpilots (NP) vs. military fighter (FP) and transport (TP) pilots. Additionally, we correlated the cardiac autonomic indices with the cardiorespiratory fitness and flight experience of FP.

METHODS: A total of 21 FP, 8 TP, and 20 NP performed a tilt test (TT), during which beat-to-beat blood pressure and heart rate were recorded.

RESULTS: No difference was detected between groups for changes in MAP and heart rate variability indices during the TT. However, the analysis of areas under the curves showed a greater increase in MAP in FP vs. TP and NP. Conversely, there was a greater decrease in indices reflecting vagal modulation in TP vs. FP and NP (rMSSD, pNN50, and SDNN), and a greater increase in heart rate and sympathovagal balance in TP vs. other groups (LF/HF). The maximal oxygen uptake was strongly correlated with the vagal reserve in FP ($r = -0.74$). Moreover, the total flying hours of FP were positively correlated with resting HFnu ($r = 0.47$) and inversely correlated with resting LFnu ($r = -0.55$) and LF/HF ($r = -0.46$).

CONCLUSION: FP had a higher pressor response to TT than TP and NP. Vagal withdrawal and sympathovagal increase induced by TT in FP were similar vs. NP and attenuated vs. TP. Greater cardiorespiratory fitness and accumulated flying hours in FP seemed to favor lower sympathetic and greater vagal modulation at rest.

KEYWORDS: $+G_z$, military aviation, aviation physiology, autonomic nervous system.

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Fighter pilots are military-trained aviators responsible for defending their country's airspace through air-to-air or air-to-ground combat. Their job is challenging due to the mechanical, chemical, and biological stressors they face continuously and concomitantly,[11] including high acceleration in the $+G_z$ axis while performing maneuvers in high-performance aircraft.[1,30]

Despite countermeasures like anti-G suits, positive pressure breathing, cockpits designed with reclining seats,[22] and the anti-G straining maneuver, during which pilots perform the Valsalva maneuver associated with repeated isometric contractions of the lower limbs to increase venous return,[1] fighter pilots still experience cardiovascular problems when dealing with the effects of high acceleration. G-induced symptoms recurrently occur, such as gray out, blackout, almost loss of consciousness, and loss of consciousness, which result from reduced cerebral perfusion.[24] The $+G_z$ forces acting in the cephalad-to-foot direction induce cerebral hypotension due to the redistribution of blood flow to lower limbs, impairing cerebral perfusion. In response, compensatory neural mechanisms that regulate the cardiovascular system are activated, such as baroreflex resetting.[1,32] Thus, the ability to make rapid cardiovascular adjustments is essential for mission success.[1]

Repeated exposure to elevated $+G_z$ can lead to alterations in the neuro-cardiovascular axis.[20] However, most of the literature

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on the physiological challenges faced by fighter pilots concerns mechanical loading during flights, resulting in neck and spine injuries.[23] Very little is known about how long-term exposure to high G-force affects the neuro-cardiovascular axis of fighter pilots. Some authors report favorable adaptations,[17,18] including increased baroreflex sensitivity,[6] while others associate regular exposure to acceleration forces with compromised autonomic responses[3,24,27] such as a higher predominance of the sympathetic nervous system.[33] Research on this subject is important because it can contribute to the development of prophylactic or therapeutic strategies to preserve pilots' health.

Several factors seem to modulate the orthostatic and G-force tolerance.[7] Although some controversy exists,[10,16] aerobic exercise training[31] and the pilots' flight experience[17,27] have been shown to increase tolerance to orthostatic stress or $+G_z$ exposure, possibly due to changes in cardiovascular autonomic regulation. Thus, investigating the relationship between cardiac autonomic modulation with fighter pilots' physical fitness and flight experience would provide insights into the determinants of an increased orthostatic and $+G_z$ tolerance.

To address these gaps, we aimed to compare the blood pressure and cardiac autonomic modulation of fighter pilots with nonpilots and transport pilots of the Brazilian Air Force at rest and during an orthostatic challenge (tilt test). We also correlated total flying hours and physical fitness levels with the cardiac autonomic indices of fighter pilots. We hypothesized that fighter pilots would have similar neuro-cardiovascular responses at rest compared to the other groups, but greater blood pressure and vagal withdrawal, as well as lower sympathetic modulation, in response to the orthostatic challenge. Additionally, we hypothesized that the cardiac autonomic indices of fighter pilots would be related to their physical fitness and flight experience.

METHODS

Subjects

Subjects were Brazilian Air Force officers, ages 20–40 yr, allocated into 3 groups according to their occupation: nonpilots (NP; $N = 20$); fighter pilots (FP; $N = 21$); and transport pilots (TP; $N = 8$). Pilots were active in flight and had an experience of more than 1500 total flying hours, while the NP group was composed of officers who operated only on the ground. Exclusion criteria consisted of: 1) smoking; 2) diagnosis of diabetes mellitus; 3) resting blood pressure ≥140/90 mmHg; and 4) body mass index ≥30 $kg \cdot m^{-2}$. All volunteers provided informed written consent before participation in the study, which complied with the recommendations established by the Declaration of Helsinki and gained approval from the Ethics Review Board of the Pedro Ernesto University Hospital (Rio de Janeiro, Brazil, CAAE 76,680,416.7.0000.5259).

Study Design

After the group allocation, subjects underwent evaluations within 2 d interspersed with 24- to 48-h intervals, always on a weekday morning (08:00–11:00) to minimize circadian effects on outcomes, in a quiet temperature-controlled environment (21–22°C). All evaluations were performed by trained technicians blinded for the study purposes and group allocation.

On the morning scheduled for the tests, volunteers presented in a 2-h fasting condition. Additionally, they were instructed to avoid physical exercise 48 h prior or ingestion of caffeine or alcohol in the 12 h before the experiment. On the first visit, after a general medical examination and anthropometric measurements, the subjects answered the International Physical Activity Questionnaire, which is a valid 27-item self-reported instrument that quantifies the level of daily physical activity.[15] Subsequently, they remained at rest in a supine position for 15 min before performing a tilt test (TT) protocol, during which beat-to-beat heart rate and blood pressure were assessed. On the next visit, the volunteers performed a maximal cardiopulmonary exercise test.

Procedures

The TT was conducted on an electric tilt table to test the cardiac autonomic control upon sympathetic stimulation induced by orthostatic stress. The subjects were instructed to remain in the supine position on the tilt table and not to perform any voluntary muscle contraction of the lower limbs and to avoid any type of movement. The TT lasted approximately 21 min and consisted of three 1-min stimuli with a passive tilt at 70° (Tilt 1, 2, and 3), followed by a 5-min recovery in a supine position after each stimulus (Rec 1, 2, and 3). The time to change the participant's position (upright and supine) was approximately 33 ± 3 s, varying with their body mass.

A treadmill cardiopulmonary exercise test was performed to assess the maximal oxygen uptake ($\dot{V}O_{2max}$), using a ramp protocol designed to elicit maximal volitional effort within 8–12 min. Respiratory gas analysis was made using breath-by-breath analysis of O_2 and CO_2 using a calibrated, computer-based exercise system (VO2000, Medical Graphics™, Saint Louis, MO, USA). The incremental test was interrupted when patients reported any discomfort preventing exercise continuity. Tests were considered as maximal in the presence of at least three of the five following criteria[12]: 1) maximum voluntary exhaustion; 2) ≥95% predicted maximal heart rate (HR; 220 – age) or presence of HR plateau (ΔHR between two consecutive work rates ≤4 bpm); 3) presence of $\dot{V}O_2$ plateau ($\Delta \dot{V}O_2$ between two consecutive work rates <2.1 $mL \cdot kg^{-1} \cdot min^{-1}$); 4) respiratory exchange ratio >1.1; or 5) a score of 10 on the Borg CR-10 scale.

Body mass and height were measured using a calibrated electronic scale (Filizola™; São Paulo, Brazil) and wall stadiometer (Sanny™; São Paulo, Brazil), respectively. Body mass index was calculated ($kg \cdot m^{-2}$).

Resting blood pressure was reported through the average of three successive measurements interspersed with 3-min pauses using an oscillometric device (Omron™ HEM 7200, Matsusaka, Japan). During TT, beat-to-beat blood pressure was continuously measured using photoplethysmography (Finometer™, Finapress Medical System BV, Enschede, The Netherlands). Beat-to-beat HR was continuously recorded at rest and during

TT through a cardiotachometer (Polar® S810i, Polar Electro OY, Kempele, Finland), and signals were transferred to the Polar Precision Performance Software (Polar Electro™). After replacing the nonsinus beats with interpolated data derived from adjacent normal RR intervals, times series data were exported to a heart rate variability (HRV) analysis software (Kubios™ HRV software, version 3.2, Biosignal Analysis and Medical Imaging Group, University of Kuopio, Kuopio, Finland). HR recording and HRV analysis in time and frequency domains were performed according to the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology.[10]

In the present study, the following indices in the time domain were assessed: standard deviation of the NN intervals (SDNN), the square root of the mean squared successive differences from adjacent RR intervals (rMSSD), and the percent number of pairs of adjacent RR intervals differing by more than 50 ms (pNN50). The SDNN reflects total variability, while rMSSD and pNN50 are estimates of short-term components of HRV reflecting parasympathetic modulation.[10] Spectral analysis was obtained and spectral power was calculated by integrating the power spectrum density function in the high- (HF; 0.15–0.4 Hz) and low-frequency bands (LF; 0.04–0.15 Hz).[10] HF is considered to reflect the parasympathetic modulation of HR, whereas LF is influenced by both sympathetic and parasympathetic activity.[10] The ratio between LF and HF was also calculated, which is acknowledged as an estimate of overall HRV and indicates the balance between sympathetic and parasympathetic influence.

Statistical Analysis

The sample size was calculated a priori by GPower™ 3.1.9.4 (Kiel University, Kiel, Germany) based on SDNN as a primary outcome, considering 80% power, 5% significance level, and an effect size of 0.25 determined by an eta squared (η^2) of medium effect size (0.06).[5] A total of 10 individuals in each group was estimated as necessary. Data normality was verified by the Shapiro-Wilk test. Data are presented as mean ± SD, or median and interquartile range if nonnormally distributed.

In all cases, a time window of 1 min in recordings was averaged and used for analysis, as follows: 1) the last minute of rest; 2) during each 1-min tilt; and 3) the first minute after each tilt. Sample characteristics, hemodynamic, and autonomic variables at rest were compared between groups by one-way ANOVA, while SDNN, rMSSD, LF/HF, and flying hours per day were compared by Kruskal-Wallis and Mann-Whitney tests, respectively. Changes from baseline in autonomic indices during TT were compared within and between groups using two-way ANOVA for repeated measures followed by Tukey post hoc multiple comparison tests in the event of significant *F* ratios for parametric data. The Friedman test was adopted for comparing nonparametric data.

Due to the probable insufficient statistical power of the two-way model, the intergroup analysis was complemented by comparing the areas under the curves (AUC) during TT using one-way ANOVA for the parametric indices and the Kruskal-Wallis test for the nonparametric indices. The associations between total flying hours vs. maximum aerobic capacity and autonomic indices were calculated using Pearson correlations for parametric indices, and Spearman correlations for nonparametric data. All calculations were performed using GraphPad™ software (Version 8.0.1, La Jolla, CA, USA) and the statistical significance level was set at $P \leq 0.05$.

RESULTS

As shown in **Table I**, there were no differences between groups for sample characteristics except for the number of days per week of flight and flying minutes per day, which were respectively higher and lower in FP compared to TP. Resting hemodynamic and autonomic outcomes are depicted in **Table II**. No difference was found between groups for HR, blood pressure, or HRV indices in the time and frequency domains.

Fig. 1 shows the changes (Δ) from baseline in HR and mean arterial pressure (MAP) for each tilt and recovery stimulus and the AUCs calculated from those responses. No main effect or interaction was found between group × time factors for HR [Fig. 1A; $F(10,215) = 0.71$; $P = 0.70$] or MAP [Fig. 1C; $F(10,215) = 0.38$; $P = 0.95$]. Comparisons of AUCs revealed that TP showed greater increases in HR (Fig. 1B) than NP ($P < 0.001$) and FP ($P < 0.001$), with no difference between NP and FP ($P = 0.78$). On the other hand, the MAP increase was greater in FP (Fig. 1D) vs. TP ($P = 0.01$) and NP ($P = 0.03$). No significant

Table I. General Characteristics of Non-Pilots, Fighter Pilots, and Transport Pilots.

CHARACTERISTIC	NP (*N* = 20)	FP (*N* = 21)	TP (*N* = 8)	*P*-VALUE
Age (yr)	33.2 (3.8)	31.3 (2.0)	31.0 (3.3)	0.15
Height (cm)	175.1 (6.3)	177.1 (5.6)	176.4 (6.1)	0.51
Body mass (kg)	80.2 (9.8)	82.4 (7.9)	81.1 (6.5)	0.53
Body mass index ($kg \cdot m^{-2}$)	26.1 (2.1)	26.2 (1.7)	26.1 (1.6)	0.84
Habitual physical activity (IPAQ)	1.8 (0.6)	1.5 (0.5)	1.9 (1.0)	0.28
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	40.9 (8.8)	40.8 (8.8)	39.7 (3.3)	0.97
Total flying hours	-	1425.0 (176.8)	1377.5 (979.8)	0.79
Number of d/wk of flight	-	*3.0 [1.0]*	*1.5 [1.0]*	0.001
Flying minutes per day	-	57.1 (4.8)	168.7 (86.2)	0.008

NP: non-pilots; FP: fighter pilots; TP: transport pilots; IPAQ: International Physical Activity Questionnaire. Continuous variables with normal distribution are presented as mean (SD); nonnormal variables are reported in italics as median [interquartile range].

Table II. Hemodynamic and Autonomic Variables at Rest of Non-Pilots, Fighter Pilots, and Transport Pilots.

VARIABLE	NP (*N* = 20)	FP (*N* = 21)	TP (*N* = 8)	*P*-VALUE
Hemodynamic variables				
HR (bpm)	59.8 (9.8)	56.4 (8.5)	61.7 (10.5)	0.45
SBP (mmHg)	117.9 (7.8)	121.2 (12.6)	122.7 (13.4)	0.51
DBP (mmHg)	63.3 (7.0)	63.0 (8.1)	65.7 (5.9)	0.73
MAP (mmHg)	81.5 (6.3)	82.4 (8.8)	84.7 (7.2)	0.64
Heart rate variability indices				
SDNN (ms)	*40.7 [29.2]*	*47.3 [47.7]*	57.0 (24.8)	0.31
rMSSD (ms)	47.0 (26.5)	*49.5 [51.1]*	63.2 (34.8)	0.46
pNN50 (%)	23.8 (19.6)	29.5 (22.6)	37.3 (25.4)	0.33
LF (ms^2)	1206.7 (1859.1)	1982.5 (2219.9)	1788.4 (1218.2)	0.10
HF (ms^2)	827.7 (703.0)	1283.0 (1678.6)	1948.0 (1785.3)	0.34
LF (nu)	55.9 (18.6)	60.7 (22.7)	55.7 (17.9)	0.77
HF (nu)	44.1 (18.6)	36.9 (21.7)	44.2 (17.9)	0.55
LF/HF	*1.2 [1.8]*	*1.7 [3.4]*	1.5 (0.9)	0.67

Continuous variables with normal distribution are presented as mean (SD); nonnormal variables were reported in italics as median [interquartile range]. NP: non-pilots; FP: fighter pilots; TP: transport pilots; HR: heart rate; DBP = diastolic blood pressure; MAP = mean arterial pressure; nu = normalized units; SBP = systolic blood pressure; SDNN: standard deviation of normal-to-normal intervals; rMSSD: root mean square of successive differences; pNN50: percent number of pairs of adjacent RR intervals differing by more than 50 ms; LF: low frequency; HF: high frequency.

difference between TP and NP was found for AUC of the MAP (Fig. 1D; $P = 0.57$).

Fig. 2 and **Fig. 3** show the changes (Δ) from baseline in autonomic indices for each tilt and recovery stimulus and the AUCs calculated from those responses. No main effect or interaction was found between group × time factors for any HRV indices for the time domain {Fig. 2; A [$F(10,230) = 0.52$, $P = 0.87$], C [$F(10,230) = 1.36$, $P = 0.19$], and E [$F(10,230) = 2.1$, $P = 0.10$]} or frequency domain {Fig. 3; A [$F(10,230) = 0.88$, $P = 0.55$], C [$F(10,230) = 0.92$, $P = 0.51$], and E [$F(10,229) = 1.42$, $P = 0.16$]}. On the other hand, comparisons of AUCs (Fig. 2B) revealed that the reduction in SDNN was greater in TP vs. FP and NP ($P \leq 0.001$), and in FP vs. NP ($P = 0.01$). As for rMSSD and pNN50 (Fig. 2D and 2F, respectively), TP showed greater reductions than NP ($P < 0.001$) and FP ($P < 0.001$), while no difference between NP and FP was found (rMSDD: $P = 0.43$; pNN50: $P = 0.93$).

The increase in LFnu and decrease in HFnu (Fig. 3B and 3D, respectively) were greater in NP vs. FP ($P < 0.001$) and TP ($P = 0.04$), with no difference between FP and TP ($P > 0.8$). Regarding LF/HF (Fig. 3F), TP presented a greater increase than FP ($P = 0.02$) and NP ($P < 0.01$).

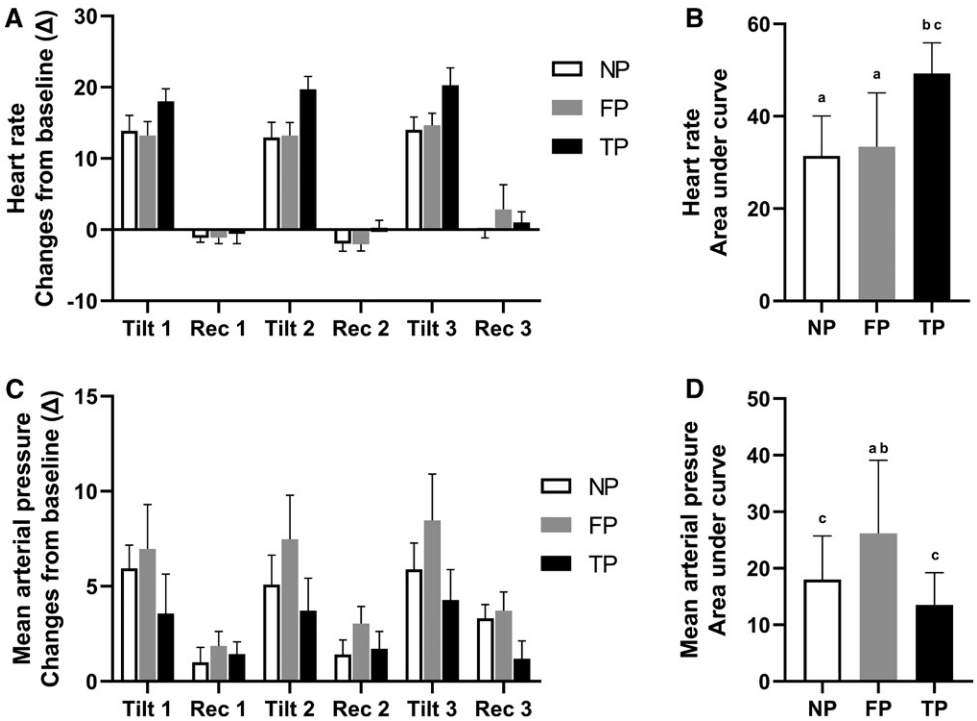

Fig. 1. Changes from baseline (A and C) and area under the curve (B and D) during tilt (1, 2, and 3) and recovery (Rec 1, 2, and 3) for HR and MAP in nonpilots, fighter pilots, and transport pilots. [a]$P < 0.05$ vs. TP; [b]$P < 0.05$ vs. NP; [c]$P < 0.05$ vs. FP.

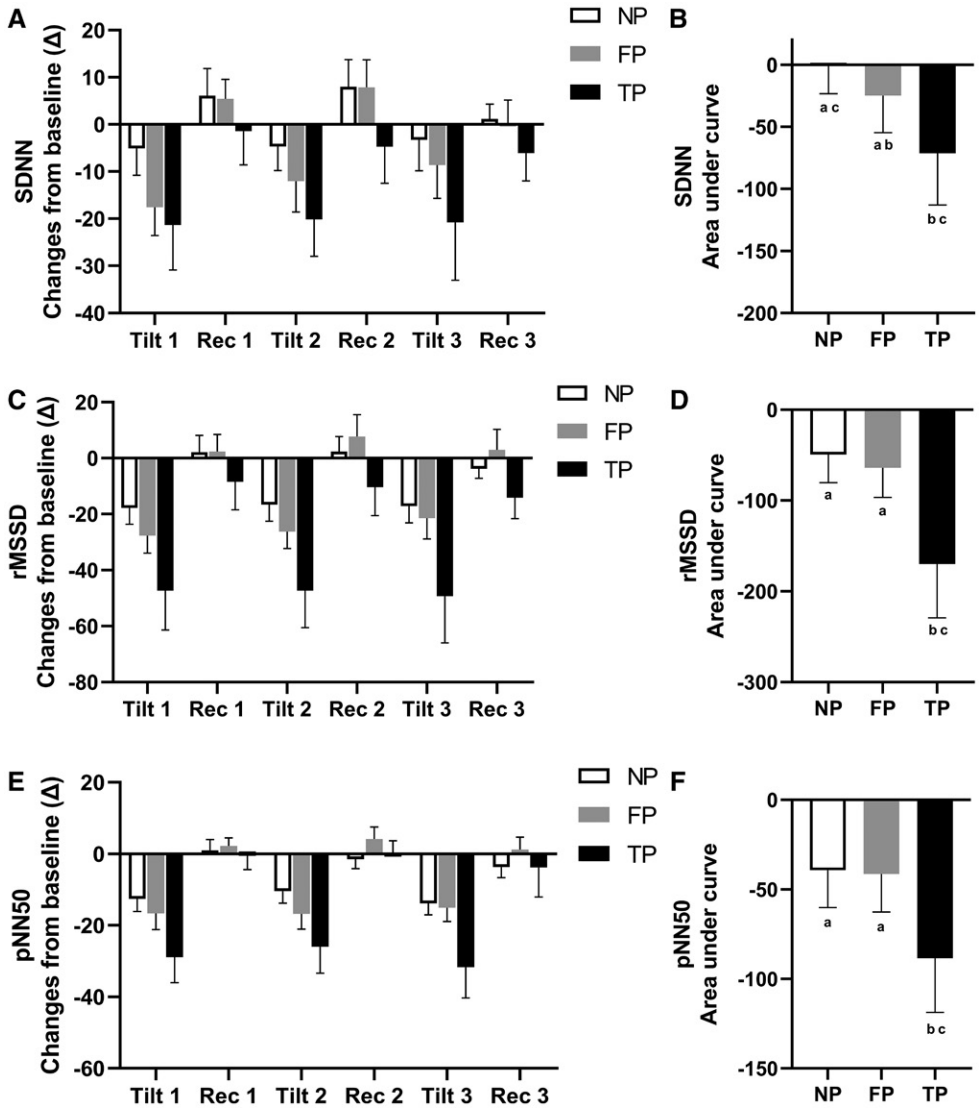

Fig. 2. Changes from baseline (A, C, and E) and area under the curve (B, D, and F) during tilt (1, 2, and 3) and recovery (Rec 1, 2, and 3) for time domain HRV indices in nonpilots, fighter pilots, and transport pilots. [a]$P < 0.05$ vs. TP; [b]$P < 0.05$ vs. NP; [c]$P < 0.05$ vs. FP.

Fig. 4 exhibits the relationship between $\dot{V}O_{2max}$ and changes from baseline to the first tilt (vagal reserve) in rMSSD of FP. A strong inverse relationship was observed between $\dot{V}O_{2max}$ and vagal reserve (R = −0.74; $P = 0.01$). **Fig. 5** depicts the correlations between total flying hours and resting autonomic indices in FP. Total flying hours was inversely correlated with LFnu (R = −0.55; $P = 0.01$; Fig. 5D) and LF/HF (R = −0.46; $P = 0.03$; Fig. 5F), and directly correlated with HFnu (R = 0.47; $P = 0.02$; Fig. 5E).

DISCUSSION

The main finding of the present study was that FP had a higher pressor response to TT than TP and NP. This response seems to rely on local vasoconstrictor mechanisms rather than cardiac autonomic modulation, as vagal withdrawal and sympathovagal balance responses to TT were attenuated in FP vs. TP, but similar vs. NP. In addition, the study expands current knowledge by originally showing that FP's experience, as expressed by the total flying hours, correlates inversely with sympathetic modulation and directly with vagal modulation assessed by frequency domain indices of HRV at rest. Furthermore, the cardiorespiratory fitness of FP is associated with changes in cardiac autonomic modulation during an orthostatic challenge.

In contrast to our results, previous research has found reduced vagal or increased sympathetic modulation at rest, during, and after stressful stimuli in FP compared to NP.[9,13,19] This suggests that regular exposure to the fighter pilot environment may lead to autonomic adaptations. However, most studies included pilots with little experience, with a wide range of flying hours (e.g.; between 400 and 1700), or did not control for this factor.[13,18,33]

Interestingly, there is evidence that the career stage of FP influences the autonomic adaptations to +G_z exposure.[17,27] Studies conducted by Sukhoterin and Pashchenko[26,27] have

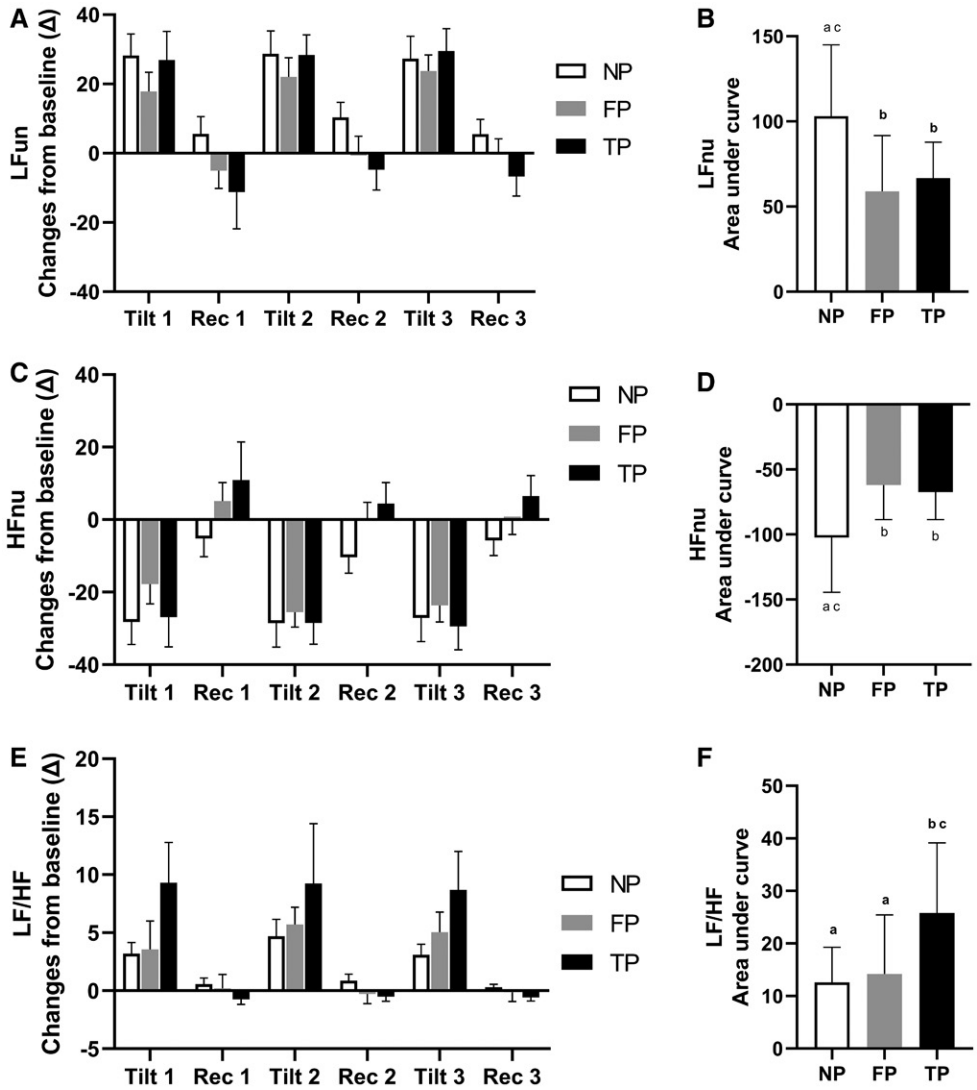

Fig. 3. Changes from baseline (A, C, and E) and area under the curve (B, D, and F) during tilt (1, 2, and 3) and recovery (Rec 1, 2, and 3) for frequency domain HRV indices in nonpilots, fighter pilots, and transport pilots. $^{a}P < 0.05$ vs. TP; $^{b}P < 0.05$ vs. NP; $^{c}P < 0.05$ vs. FP.

demonstrated that vagotonia at rest would be greater in more experienced vs. novice FP. Another trial[26] demonstrated that subjecting rats to acute gravitational loads resulted in reactive changes in the central autonomic nuclei. With repeated exposure, these changes became progressively destructive, resulting in the depletion of nucleate chromatin, a reduction in electron density within the mitochondrial matrix, and homogenization of mitochondrial cristae. Therefore, it is feasible to speculate that changes in sympathovagal modulation along the FP career might result from a depletion of sympathetic reserves that are constantly activated due to high accelerations, leading to chronic damage of the involved structures. Our results reinforce this hypothesis, as the total flying hours among FP correlated with indices of resting autonomic modulation, especially in the frequency domain. In other words, within-group correlation analysis demonstrated that FP with longer experience expressed by the accumulated flying hours tended to exhibit higher vagal and lower sympathetic modulation at rest.

This relationship between exposure to high accelerations and cardiac autonomic control may help to explain the attenuated autonomic responses to TT in FP vs. TP. As the average total flying hours of FP were generally higher than those presented in previous studies,[16,33] this factor may have influenced our results. However, it must be considered that the comparison between groups admitted the average behavior of FP, which had pilots with different levels of experience and +G_z tolerance. The higher SD values for the resting autonomic control in FP vs. TP and NP reinforce that the interindividual variability of pilots' experience may have contributed to the attenuated autonomic response to TT and the lack of difference between groups at rest.

Another possible explanation for the lower cardiac autonomic responses of FP vs. TP to TT could be a greater dependence on local regulations of blood flow, such as myogenic activation of vascular smooth muscle, to increase blood pressure levels rather than cardiac autonomic changes. Our MAP

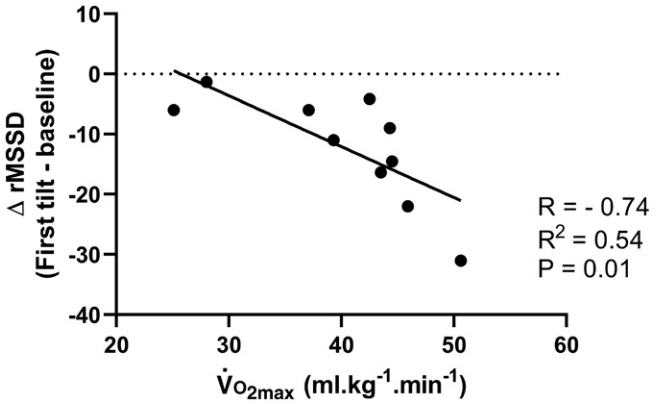

Fig. 4. Correlation between maximal aerobic capacity ($\dot{V}O_{2max}$) with changes in rMSSD from rest to 1st tilt in fighter pilots ($N = 10$).

and HR data reinforce this hypothesis. Consistent with our findings, previous research[16,18] reported similar stroke volume and HR, but greater blood pressure gains and peripheral vascular resistance (PVR) in FP than NP during TT. Another trial[28] demonstrated that individuals with high vs. low tolerance to +G_z had greater arterial stiffness and PVR during sympathetic activation, potentially due to increased myogenic responsiveness in precapillary vessels. The blood pressure increases under stress conditions in individuals with high tolerance to +G_z would result from a greater local vasoconstrictor reserve, while for those with low tolerance to +G_z this response would mainly rely on central mechanisms (cardiac output and stroke volume). However, the lack of trials investigating the hemodynamic responses to TT in FP hinders further insights into the contribution of central and intrinsic vascular factors to blood pressure changes during the orthostatic challenge in this particular population.

We observed a direct association between the pilots' cardiorespiratory fitness and vagal withdrawal after tilt stimulus. A recent review[21] reinforced the assumption that aerobic conditioning provokes autonomic adaptations, increasing parasympathetic and decreasing sympathetic activity at rest, which also seems to occur during orthostatic challenge in nonpilot militaries.[31] Prior evidence indicates that aerobic training also increases the postexercise vagal reentry even without changes in vagal tone at rest, especially in individuals exhibiting lower resting vagal tone at baseline.[8] However, most studies failed to demonstrate adaptations resulting from exercise training on +G_z tolerance among FP.[14,25] Slungaard et al.[25] investigated the effect of 12-wk physical training on G-force tolerance in a human centrifuge and found no differences in blood pressure between trained and control groups. Similarly, in a cross-sectional design, Kölegård and Mekjavic[14] found no differences when comparing +G_z tolerance and pressor response to exercise in sedentary, endurance-, and strength-trained individuals. Interestingly, those authors hypothesized that during +G_z exposure individuals performed anti-G straining maneuvers, activating muscle mechano- and metaboreflex to maintain blood pressure levels. However, we could not find studies on the effects of physical training on autonomic control or muscle metaboreflex sensitivity in association with +G_z tolerance.

Unexpectedly, when compared to NP and FP, TP showed greater vagal withdrawal and sympathetic modulation expressed by the LF/HF ratio in response to TT. Exceptions were the LF_{nu} and HF_{nu} indices, which may have been influenced by slower recovery from TT. Since there were no differences between the groups for cardiorespiratory fitness, habitual physical activity, and autonomic control at rest, we believe that these differences may be due to specific adaptations resulting from the occupational activities in TP, such as lower flight frequency and longer missions in comparison to FP. Regarding flight duration, Dussault et al.[9] evaluated the sympathovagal balance before and after 2 h of long vs. short combat flights and showed that the autonomic response could differ depending on the mission characteristics. After shorter flights, the sympathovagal balance, as expressed by LF/HF increased, while it decreased after longer flights. Similar results were found by Jouanin et al.,[13] who identified that short flights (30 min) induced an increase in LF/HF up to 2 h after the mission. However, it should be noted that these findings are limited since there was no comparison with a control group exposed to the same stressor (+G_z).

Few studies have investigated the autonomic behavior of pilots during flight or in sympathetic stimulation protocols. Among those that used TT, prolonged stress-mediated orthostatic changes were the most commonly adopted protocols,[2,9,13] consistent with research conducted in other populations.[4,29] In the present study, we chose a protocol that involved successive short passive tilts to better mimic the incremental and irregular blood flow redirection stimuli experienced during flights. In this case, analyzing the areas under the curves seemed ideal, as it allows for insight into both the response to stimuli and recovery.

This study has both strengths and limitations. One limitation is the relatively small sample size in the TP group ($N = 8$), which was inferior to the estimated sample size. The difficulty in recruiting this group due to flight schedules resulted in a discrepancy in the number of individuals included in the FP ($N = 21$) and NP ($N = 20$) groups. On the other hand, the FP sample was much greater than in most available research, which is undoubtedly a strength of our study. Moreover, FP with different experience levels were compared not only to NP but also to military pilots who typically perform significant flight volumes (TP) but do not undergo intense +G_z stress. Secondly, respiratory rate was not assessed during the assessment of RR intervals. However, subjects were instructed to maintain relaxed normal breathing—typically around 12–20 breaths/min. This may have lessened the potential effects of respiratory rate on our HRV data, although we cannot completely rule out this possibility. Another major limitation was the duration of TT. Previous studies adopted protocols in which the time to change the tilt table position was approximately 4 s,[16,17] while the present experiment applied a much longer duration (around 33 s). This may have influenced our findings since faster stimuli would be more similar to hemodynamic stress in flight conditions.[17] Finally, the lack of a more robust cardiovascular and

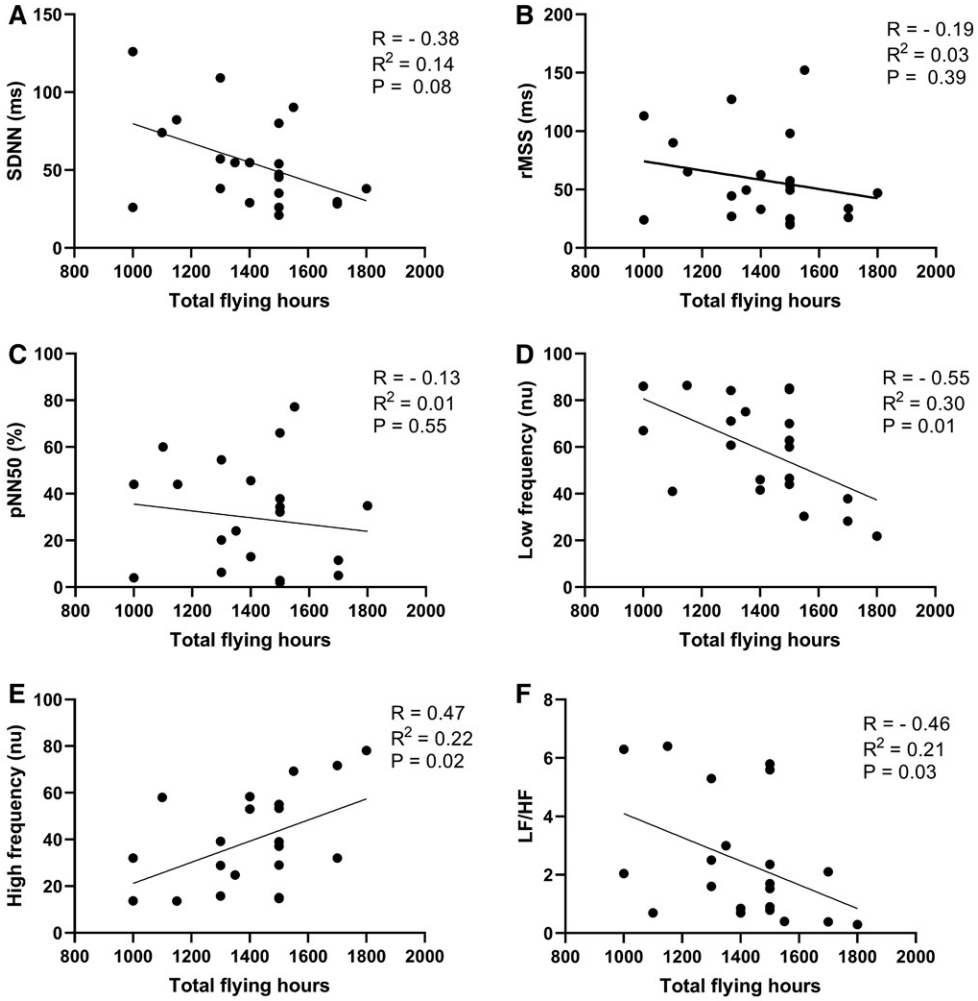

Fig. 5. Correlation between total flying hours with indices of resting HRV for the time domain SDNN, rMSSD, and pNN50 (Panels A, B, and C) and frequency domain LFnu, HFnu, and LF/HF (Panels D, E, and F) in fighter pilots ($N = 21$).

sympathetic activity assessment should be mentioned. Data on the cardiac baroreflex sensitivity, cardiac output, PVR, and muscle sympathetic nerve activity during TT could have given a better understanding of the neuro-cardiovascular responses. Although HRV has the advantage of being a simple, noninvasive method capable of assessing dynamic changes in the autonomic control of heart rate,[10] more objective measurements of sympathetic outflow, such as microneurography, would provide more specific and direct information on sympathetic activity at the periphery.

In conclusion, FP with an average of 1425 flying hours showed a higher pressor response, but a modest response to autonomic activation when subjected to TT. This was reflected by lower vagal withdrawal and sympathetic gain compared to TP. On the other hand, the autonomic responses in FP were generally similar to those in NP. Additionally, the autonomic modulation at rest among FP appeared to be influenced by cardiorespiratory fitness and accumulated flying hours. Greater aerobic capacity and flight experience were strongly associated with higher vagal and lower sympathetic modulation in this group. These findings are relevant because they can contribute to interventions and decision-making regarding the operational training and health preservation of military pilots. However, our data should be considered preliminary and must be confirmed by further research, including larger samples and a longitudinal approach.

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